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Nurturing Our Satellite Space Workforce at the United States Air Force Academy

Kenneth E. Siegenthaler,^{*} Timothy J. Lawrence,[†] Daniel A. Miller, II,[‡] David E. Swanson,[§]
Maarten J. Meerman,^{**} David J. Barnhart,^{††} Matthew Geoff. McHarg^{‡‡}, and Jim White^{§§}
United States Air Force Academy, Colorado, 80840

The Space Systems Research Center at the United States Air Force Academy is building a cadre of satellite space professionals “one cadet at a time.” Its motto and aim is for cadets to “Learn Space by Doing Space.” Approximately one half of the cadets majoring in astronautical engineering perform a one year long capstone program covering the design, fabrication, test, launch and operation of a satellite into space (the FalconSAT program). FalconSAT-2 is a 19.5-kg satellite scheduled to launch on the SpaceX Falcon I launch vehicle in October of 2005 from Kwajalein Island in the South Pacific. The cadets are currently working on FalconSAT-3, a 50-kg satellite expected to launch in 2006 on an Atlas V. Both missions have payloads approved by the Department of Defense Space Experiments Review Board to conduct space-weather experiments and Air Force Research Laboratory avionics and propulsion experiments. This program works just like any Air Force program, with the cadets being the contractor and the faculty and Air Force funding agencies being the Air Force Manager. The program has approximately 25 students, with six to eight faculty mentors. FalconSAT is a multi-disciplinary program, including cadets majoring in physics, electrical engineering, mechanical engineering, computer science, and management. All of the normal milestones, reviews, presentations, and reports required in an Air Force program are required of the cadets in this program. The cadets do all of the briefing. The cadets also do all of the hands-on work including clean room manufacturing and assembly, and bake out and vibration testing. It is a true cadet run program with faculty mentors to keep things on track. The current goal is to launch a new satellite every two to three years. After presenting the development, challenges, and advantages of conducting an undergraduate space program performing world class research, this paper details the cadet construction, testing, and preparations for the October 2005 launch of FalconSAT-2.

I. Introduction

THE Space Systems Research Center (SSRC) program at the United States Air Force Academy (USAF) is building a cadre of space professionals “one cadet at a time.” The program gives cadets the opportunity to “Learn Space by Doing Space” through a capstone course in the Astronautics Department. This program allows cadets to gain real-world experience with satellite system design, assembly, integration, testing, and operations within the context of a two-semester engineering course. It provides a practical platform for Air Force and Department of Defense (DoD) space experiments. The USAF Academy started experimenting a decade ago with small satellites via cadet-built prototypes “launched” on high altitude balloons to 30,000 meters. These projects

^{*} Associate Professor, Department of Astronautics, Senior Member AIAA.

[†] Assistant Professor and Director of the Space Systems Research Center, Department of Astronautics, Member AIAA.

[‡] Associate Professor, Department of Astronautics, Member AIAA.

[§] Assistant Professor, Department of Astronautics, Member AIAA.

^{**} General Bernard A. Schriever Chair, Department of Astronautics, Associate Fellow AIAA.

^{††} Assistant Professor, Department of Astronautics, Member AIAA.

^{‡‡} Professor and Director of the Space Physics and Atmospheric Research Center, Department of Physics.

^{§§} Technical Consultant, Department of Astronautics, Member AIAA.

gave the students immediate, hands-on experience and inspired the Department of Astronautics to evolve the curriculum to accommodate increasingly more ambitious space projects. A major milestone was the launching of FalconGold, a 15 kg fixed, secondary payload on an Atlas-Centaur launch vehicle in 1997. FalconSAT-1 was a 52 kg satellite launched on a Minotaur. The learning experience of the cadets designing, fabricating, testing, launching and operating these satellites guided the Department of Astronautics in developing a reproducible program for cadets to launch a new satellite every two to three years. Fig. 1 illustrates the size of a typical class. The recent and future milestones of the satellite program are summarized in Table 1.



Figure 1. The typical size of a FalconSAT team.

Table 1. Summary of FalconSAT program milestones².

DATE	LAUNCH VEHICLE	SATELLITE / SIZE	MISSION
May 1995	Balloon Flight	USAFASAT-B	Attitude Control Demonstrator
Mar 1996	Balloon Flight	Glacier	GPS & Magnetometer Experiment
Sep 1996	Balloon Flight	PHOENIX	Laser Communication Demo
Apr 1997	Balloon Flight	FalconGold / 15kg	GPS Signal Capture
Oct 1997	Atlas - Centaur	FalconGold / 15kg	GPS Signal Research
Jan 2000	Minotaur	FalconSAT-1 / 52 kg	Spacecraft Charging Hazards Research
Ready for Launch	SpaceX Falcon I	FalconSAT-2 / 19.5 kg	Ionosphere Plasma Bubble Research
Projected 2006	Atlas V	FalconSAT-3 / 50 kg	Ionosphere Plasma and Attitude Control Propulsion Research

II. The Standardized FalconSAT Program^{1,2,3}

With almost 100% cadet turnover every year, standardization is essential for a successful FalconSAT program. This infrastructure includes a flexible platform that can be readily adapted and enhanced to meet future payload requirements and secondary launch opportunities. Part of this approach is to use commercial off-the-shelf hardware within budget and time constraints. Although such purchases ease the design problem in many respects, considerable effort remains in the areas of payload design and development, structures, attitude control, thermal control, solar panels, testing, and operations—more than enough to challenge even the most ambitious undergraduate students.

Involving cadets from a variety of departments, not just Astronautics, expands the knowledge base of the participants and gives every cadet a priceless opportunity regardless of academic major. This approach better reflects how technical programs in the Air Force are conducted, involving engineers, scientists, managers, technical writers and other experts from a variety of fields. Teaming scientists with a keen interest in designing space experiments with engineers who want to build missions provides great synergy to the program. For example, the experiment flown on FalconSAT-1 was conceived and built by faculty and students from the USAF Academy's Physics Department. Since then, select computer science, electrical engineering, mechanical engineering, and management majors have joined the program. This partnership has not only given an interesting scientific focus to the missions, but has brought them real-world credibility. The experiments on all FalconSAT missions compete for recognition across the Department of Defense (DoD) for approval by the DoD Space Experiments Review Board (SERB). Such credibility gives the added bonus of critical additional funding and all-important space launch opportunities.

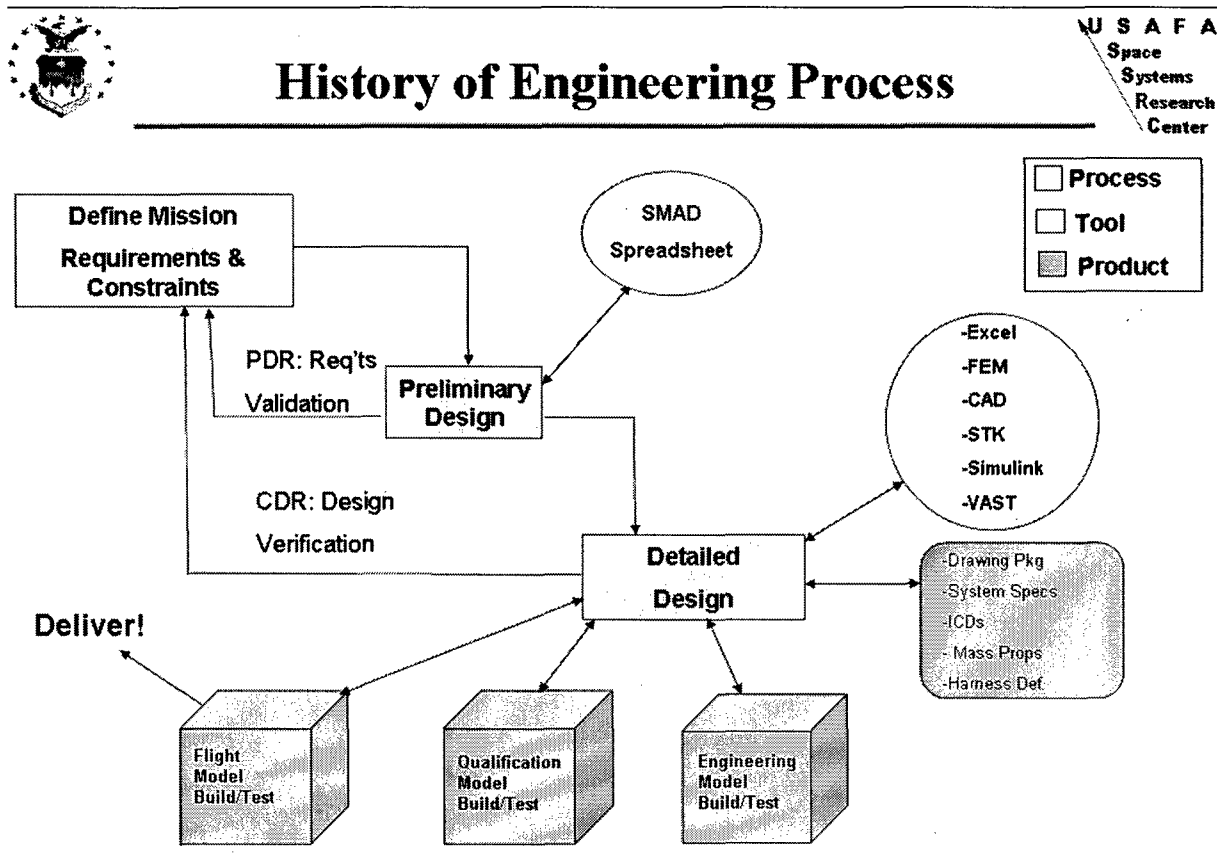


Figure 2. Systems engineering process.

With this real-world focus, real-world funding, and real-world visibility, it has become ever more important to run the program using real-world tools. Chief among these are rigorous systems engineering processes including

technical reviews. The DoD mandates a tailored acquisition sequence for all its programs that closely follows the IEEE *Standard for Application and Management of the Systems Engineering Process*⁴. This process begins with requirements analysis and culminates in system deployment. This systems engineering process in combination with a Gant chart with milestones is essential to the success of the program. Along the way, major milestones in the form of formal technical reviews are conducted. As seen in Fig. 2, in addition to multiple status reviews these milestones include Preliminary Design Review (PDR), Critical Design Review (CDR), and Final Readiness Review (FRR).

It should be emphasized that the cadets do *all* the briefing, including the many informal and semi-formal status reviews conducted throughout the program. The Preliminary Design Review (PDR) is a formal briefing with the objective of gaining permission to proceed with the fabrication and test of subsystems. The cadets are not allowed to acquire materials or begin construction until all action items are closed from the PDR. This review forces the cadets to have a detailed and well thought out design before committing funds and effort to fabrication and testing of subsystems. Encountering the importance of cost is a shock to students accustomed to using textbook solutions. This practicality begins a maturing process for many young engineers and introduces them to the importance of maintaining good relationships with the management side of the program. It also introduces them to the complexity of a program and the tremendous responsibilities and pressures on a program manager. They thus come to understand the problem of how to produce a successful program on time and under budget.

The Critical Design Review (CDR) is a formal, multi-day briefing to reviewing experts from outside of the Air Force Academy. These reviewers included personnel from the Air Force Space and Missile Center, Air Force Research Laboratory, Aerospace Corporation, Lockheed Martin, and Boeing. The objective of the CDR is to gain permission to proceed with the integration of all subsystems and the performance of operational/field testing of the total system. As usual the cadets are the briefers—which amounts to an oral examination of their project. Just as teachers really learn a subject when required to teach it, being subjected to questions throughout the student's briefing by outside experts stimulates increased understanding of the subject – hopefully before the briefing, but always afterwards.

The Final Readiness Review (FRR) is the equivalent of the Prototype Acceptance Demonstration in the DoD procurement program. The FRR is a formal review ensuring that all the requirements of the program have been fulfilled. It includes the thermal bake-out testing, the shake test, etc. This review is presented to the same reviewing experts as the CDR. Satisfactory completion of this review means the satellite is ready to be launched.

By its nature, any design class is open ended and difficult to program lesson-by-lesson compared to a traditional lecture-based course. However, by requiring students to follow prescribed, industry-standard systems-engineering processes, some formal structure can be imposed on the semester and the design reviews serve as major deliverables for grading purposes.

The FalconSAT program requires the cadets to build three models of the satellite during the satellite development for a single mission. First, an Engineering Model (EM) is built to make sure all of the components fit and are compatible with the mission. Next, a Qualification Model (QM) is constructed, which has all of the characteristics of the Flight Model (FM) and is tested to above the limits for all aspects required of the FM. Finally, the FM is fabricated, which is the satellite that will be flown in space. Each model of the satellite must complete the entire review process through FRR before starting the fabrication and testing of the next model of the satellite. Building three satellite models reduces the risk of failure and gives each cadet class a hands-on hardware experience. Because of the academic setting, the overall budget is an order of magnitude less than accomplishing the same program commercially. For more details on the FalconSAT program see references 1, 2, 3 and 4.

III. The FalconSAT-2 Program

A summary of the FalconSAT-2 Mission Architecture is shown in Figure 3. As the FS-2 program is covered in more detail, the nearly 100% turnover of cadets in the class will emphasize the importance of detailed documentation by the work of each class. FalconSAT-2 is designed to accomplish three main mission objectives:

1. The primary science objective is to investigate ionosphere plasma depletions that cause radio transmission disruptions. This will be accomplished using the miniature electrostatic analyzer (MESA) instrument onboard the FalconSAT-2 spacecraft, which represents a DoD Space Experiments Review Board (SERB) mission.
2. The overall programmatic objective is to provide an opportunity for USAF Academy Cadets to “learn space by doing space,” allowing them to participate in all phases of mission design, assembly, test and operations.
3. A final, longer-term objective is to validate key technologies, design concepts, and processes that can be used for follow-on FalconSAT missions.



FalconSAT-2 Mission Architecture

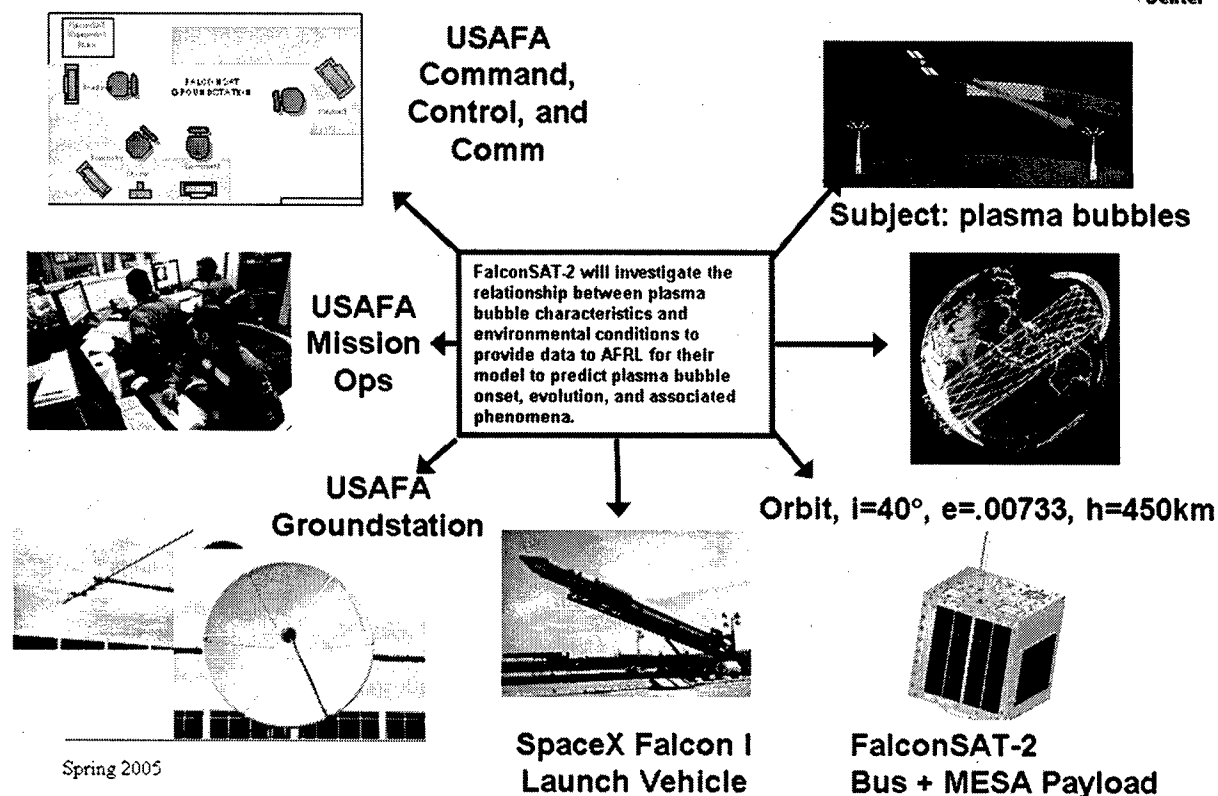


Figure 3. The FalconSAT-2 Mission Architecture.

FalconSAT-2 (FS-2) is a 19.5 kg cubical satellite that is 32 cm on each side as illustrated in Fig. 4. The scientific research payload is a Mini Electro-Static Analyzer (MESA) to investigate low latitude ionospheric plasma bubble depletions and their effects on radio waves, e.g., GPS signals. It has been observed that the interference with the propagation of certain frequencies of radiowaves corresponds with the production and depletion of plasma bubbles in the ionosphere. The exact correlation and mechanisms is not fully understood. The collection of additional data for analysis is needed for confirmation of various proposed theories. The MESA experiment on FS-2 will establish a flight heritage for the MESA instrumentation system as well as collecting additional plasma data. The MESA instrumentation and experimental planning was accomplished by cadets and faculty in the Physics Department. This experiment was rated as #21 out of 34 selected by the DoD Scientific Experiment Research Board (SERB).

Each year, the class is divided into various teams (such as the Power Team, Structures Team, etc.). Each class period starts with a 10 to 15 minute meeting of the entire team, during which each team gives a brief status report. This ensures that everyone is knowledgeable of the status of the program at all times. A class period is two hours long and each cadet is expected to spend at least four hours of work outside of class for every class period. Many spend more time than required to accomplish the mission.

The Engineering Model (EM) phase of the program was complete in April, 2001. This phase included the design, fabrication and testing of the Engineering Model. The testing included about 20 cadets traveling for a week to Albuquerque, New Mexico to conduct a vibration test on the shaker table (shown in Fig. 5) at the Air Force Research Laboratory. This work was completed by the cadet class of 2001.

The Qualification Model (QM) phase of the program was completed in February, 2002. This phase included the design, fabrication and testing of the Qualification Model (See Fig 6.). The testing included a random vibration test exceeding Shuttle loads by 6dB with sine bursts in all three axes. In addition, the satellite was subjected to thermal

vacuum testing with five thermal cycles from -20°C to $+50^{\circ}\text{C}$. These tests were conducted by about 20 cadets over a two week period at the Air Force Research Laboratory testing facilities at Kirtland Air Force Base, New Mexico (shown in Fig. 7). This work was completed by the cadet class of 2002.

The Flight Model (FM) phase was completed in July of 2002. This phase included the design, fabrication and testing of the Flight Model (See Fig 8.). The testing included a vibration test as well as a thermal vacuum test. Again, these tests were conducted by about 20 cadets over a two-week period at the Air Force Research Laboratory testing facilities at Kirtland Air Force Base, New Mexico (shown in Fig. 9). Center of Gravity and Moment of Inertia tests were also conducted at Kirtland Air Force Base. This work was also completed by the cadet class of 2002.

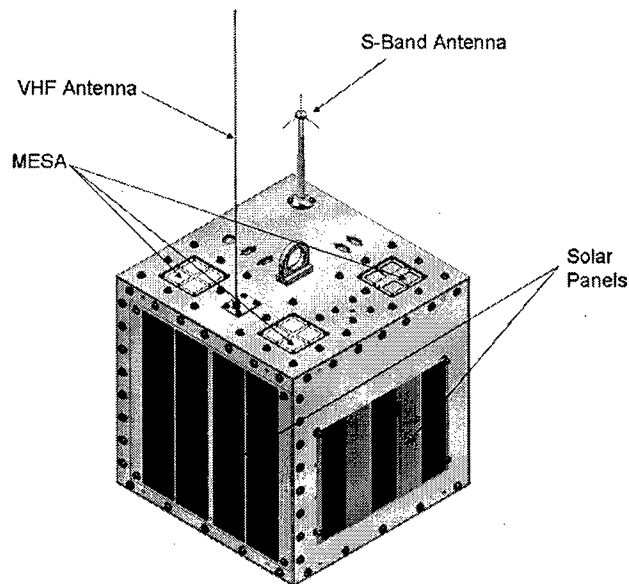


Figure 4. FalconSAT-2.

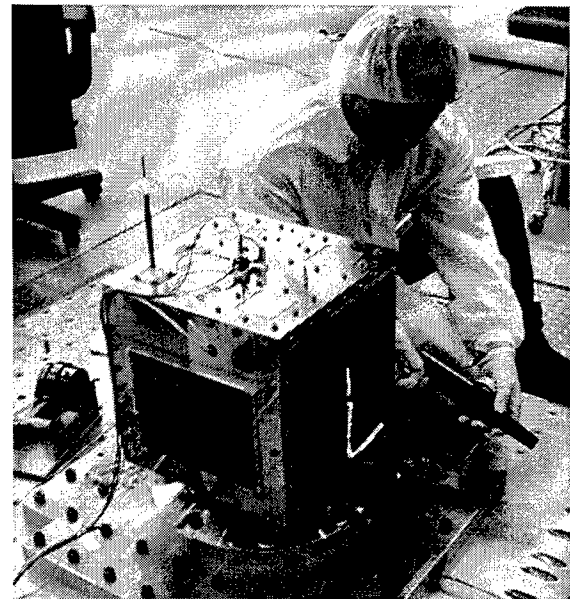


Figure 5. Vibration testing of FalconSAT-2 on the Air Force Research Laboratory Shaker Table.

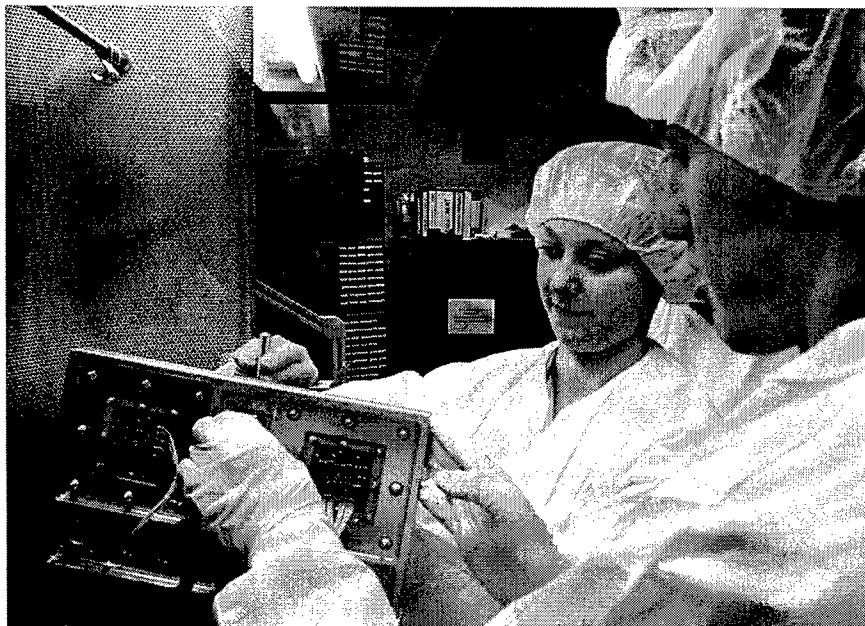


Figure 6. Cadets assembling the FalconSAT-2 Qualification Model.

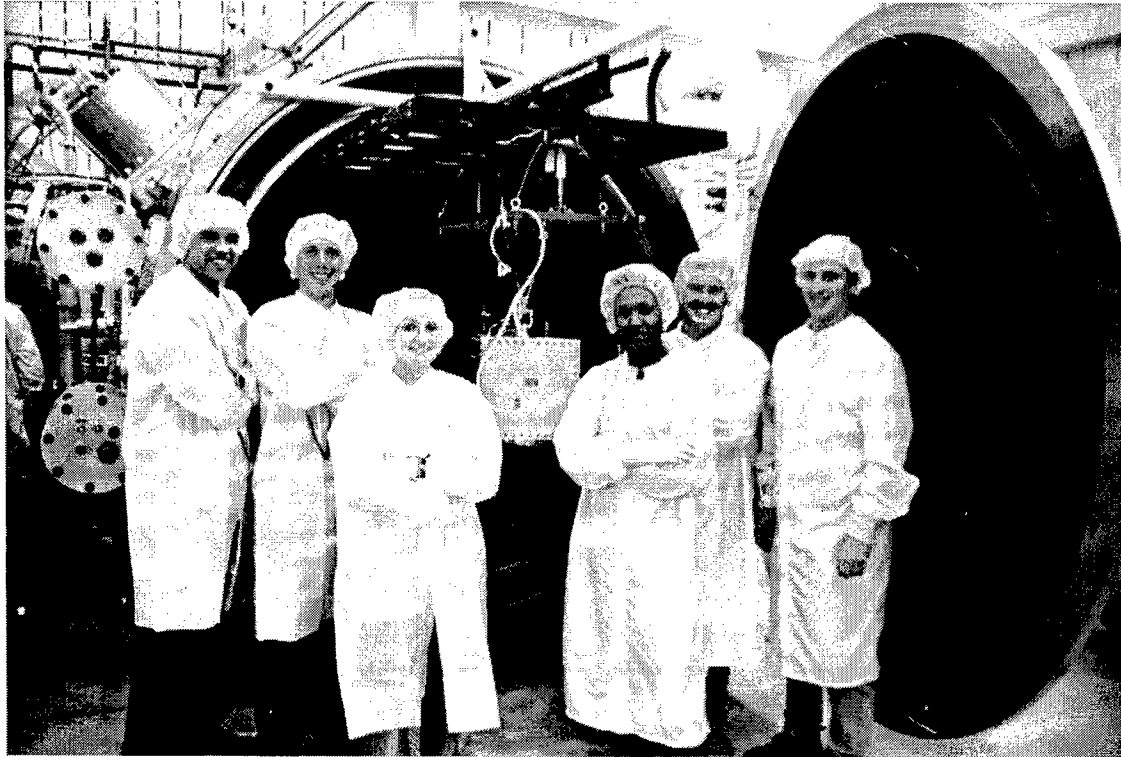


Figure 7. Part of the FalconSAT-2 team performing thermal vacuum testing on FalconSAT-2.

FalconSAT-2 was scheduled to be launched from Cape Canaveral on Shuttle Mission 108. This, unfortunately, was the next mission after Shuttle Mission 107, which had the disastrous reentry. FS-2 was put on hold until in January 2005, when it was manifested to launch on the Space Exploration Technologies (SpaceX) Falcon 1 launch vehicle. The launch is scheduled for October of 2005 from the Kwajalein Atoll in the Pacific Ocean. SpaceX is developing new low-cost (\$6M plus range fees), high-reliability launch systems. Falcon 1 is the first launch vehicle that they have designed, and FalconSAT-2 will be the first launch of a SpaceX Falcon 1. Because of the change in launch vehicles, FalconSAT-2 was required to be recertified for flight. This required a vibration test, fit check, creation of an Interface Control Document, and a separation test. The separation test shown in Fig. 10 was conducted at the SpaceX facility in California. The storage, modifications and recertification of FS-2 were accomplished by the cadet classes of 2003, 2004 and 2005.

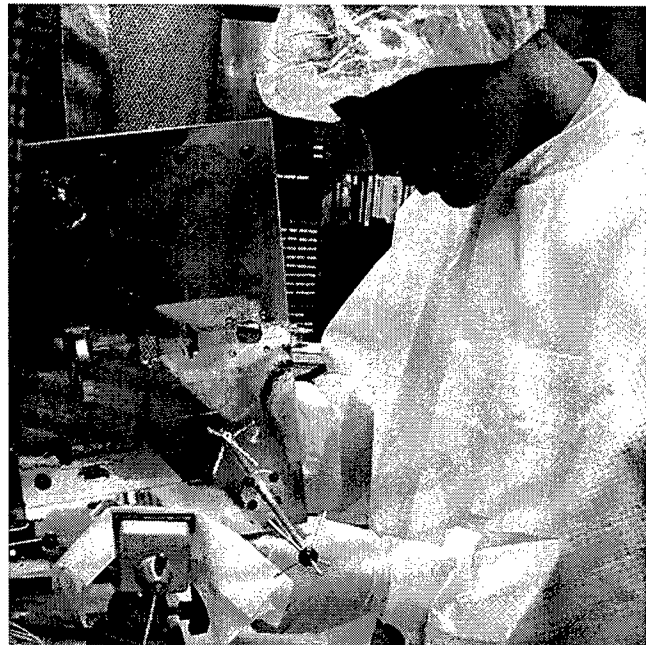


Figure 8. A cadet assembling the communications antenna for FalconSAT-2.

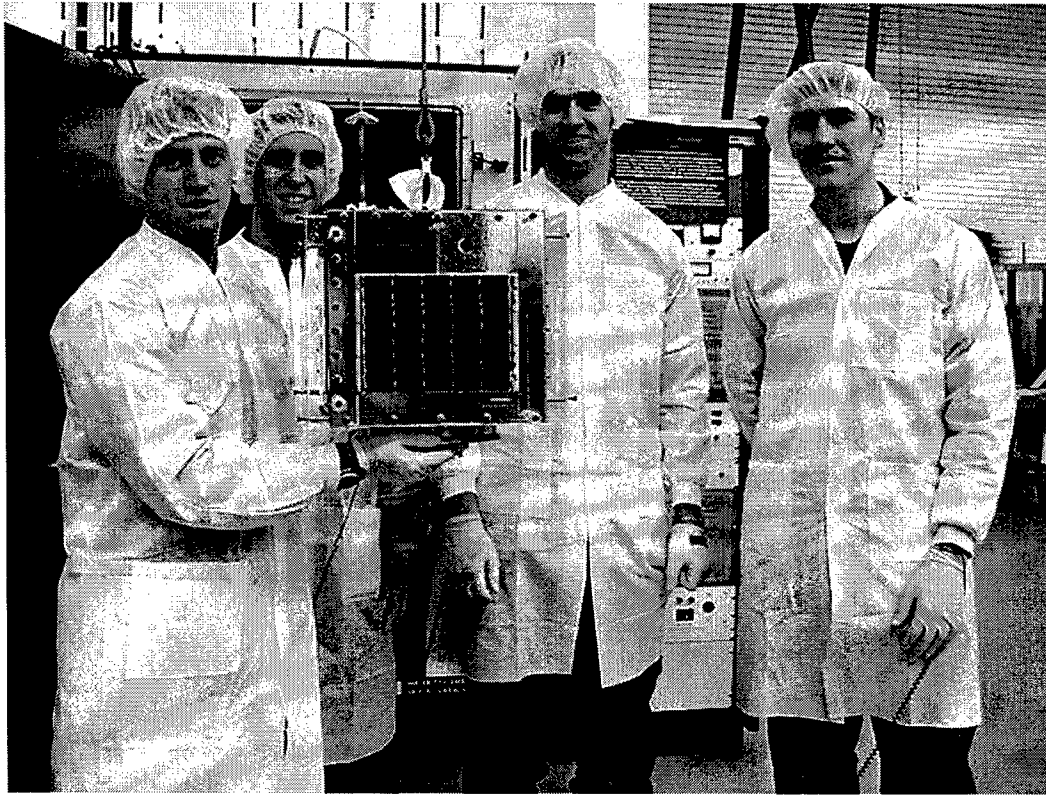


Figure 9. Cadets moving FalconSAT-2 from the thermal vacuum test to the shaker table.



Figure 10. Cadets conducting the separation test at the SpaceX facility in California.

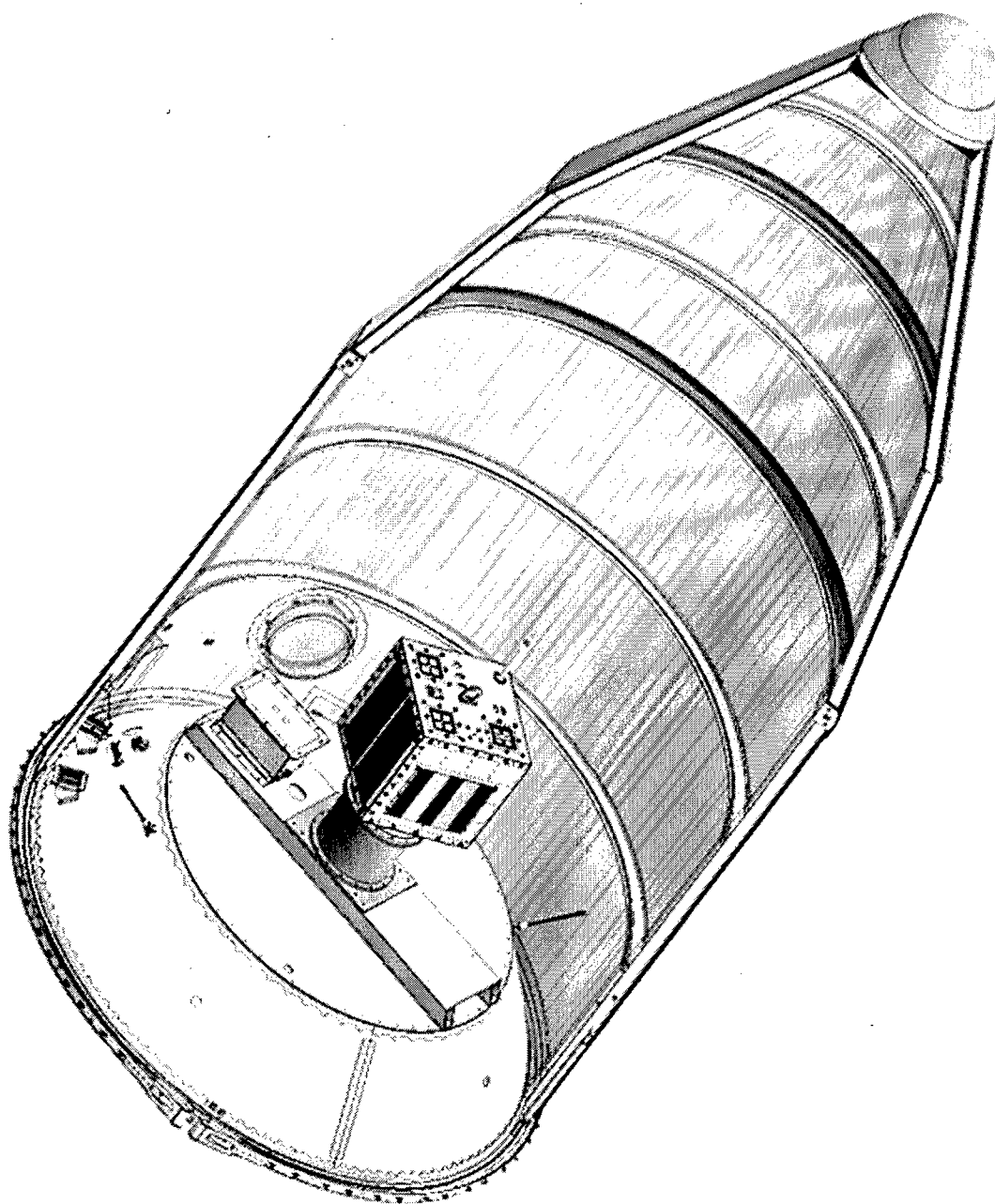


Figure 11. FalconSAT-2 payload integrated inside the SpaceX Falcon I launch vehicle.

The deployment of FalconSAT-2 to Kwajalein Atoll, launching, and space operations of FS-2 will be accomplished by the cadet classes of 2006 and 2007. FalconSAT-2 will be flown on a C-17 to Kwajalein Atoll for launching. The present projected launch date is in October, 2005, from the Reagan Test Site. FalconSAT-2 is the only payload on the Falcon 1 launch vehicle and is positioned as illustrated in Fig. 11.

The SpaceX launch vehicle will place the FS-2 spacecraft in a 300 by 400 km elliptical orbit tilted 40 degrees to the equator (see Figures 12 and 13). After orbit insertion, FS-2 will be operated by cadets working in the FalconSAT Ground Station located at the United States Air Force Academy (USAFA), Colorado Springs, Colorado. In addition to the design and manufacture of the satellite, for three years the Space Operations component of the FalconSAT-2 class has been preparing to control FS-2. Senior cadets from the classes of 2003, 2004, and 2005

created and perfected the processes and procedures required to commission and maintain the space vehicle. They left a legacy of quality documentation, tested checklists, and proven training plans that will be used by the class of 2006 to conduct satellite operations.

Satellite operations at USAFA were developed on the model used by Air Force space operations squadrons. In order to “Learn Space by Doing Space” cadets were organized into a Cadet Space Operations Squadron (CSOPS). The leadership structure consisted of a cadet Squadron Commander (CC) and cadet Director of Operations (DO) under which exist three divisions: the Training Division (DOT) that is responsible for developing and implementing a training program, the Standardization and Evaluation Division (DOV) that is responsible for maintaining squadron standards and assessing a cadet’s ability to operate the satellite, and the Current Operations Division (DOX) that is responsible for maintaining all operationally relevant documentation, for running the unit’s operational review process, and for overall scheduling. Ultimately, the squadron exists to operate an on-orbit asset—FS-2.

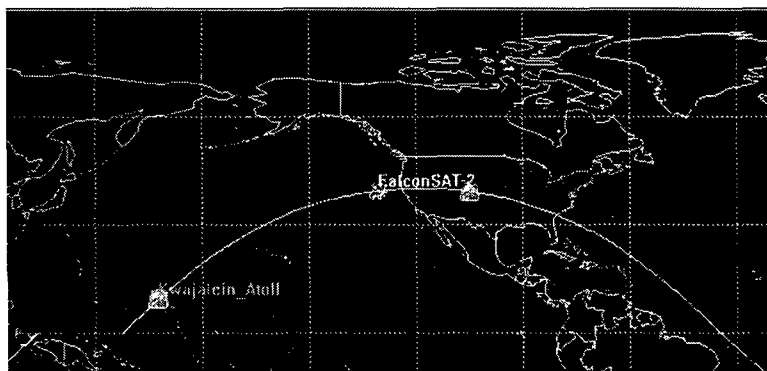


Figure 12. The launch trajectory of FalconSAT-2 from the Kwajalein Atoll.

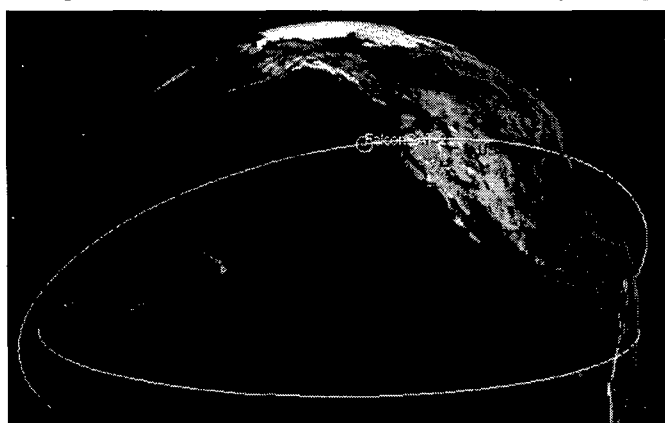


Figure 13. The FalconSAT-2 orbit.



Figure 14. The cadet Space Operations squadron patch.

Management aside, the real work is done by crews of trained and certified operators. Each crew is composed of three positions. The Satellite Operations Officer (SOO) who is the spacecraft expert on the crew. This person understands the telemetry radioed down to the ground site. He/she knows how the space vehicle is supposed to be configured, and if the satellite is in an anomalous situation the SOO is the first to recognize it and offer a solution. The second position is the Ground Control Officer (GSO) who fully understands the ground equipment. This officer is responsible for contacting the satellite and maintaining the radio link between it and the station. If the link is broken, the GSO will respond and re-establish contact. The last position is that of the Crew Commander (CMDR). It is this officer’s job to run the crew shift, establish a working pace for the crew during a satellite pass, and ensure all mission requirements are met.

The FalconSAT operations program, called FalconOPS, requires cadets to organize and manage themselves. The principle objective is to turn college thinkers into space leaders. Cadets are given a “Commander’s Intent” and let go. Faculty are involved as mentors rather than instructors. Initially the cadets struggle to understand their new roles, but after a month they begin to take ownership of the program. Each class is unique and each has a unique way of operating, but all end the school year in high gear. The three seniors in the 2004 class trained eight cadets and three of the faculty in operations. The following year, nine 2005 senior cadets improved the training program

and trained themselves, 12 other cadets, and two of the faculty. As a result of all this work, there are three fully trained crews ready for the FS-2 launch today with two additional crews expected by the FS-2 launch rehearsal in September, 2005. FS-2 will take flight in the fall but the FalconOPS program has been flying high for three years.⁵

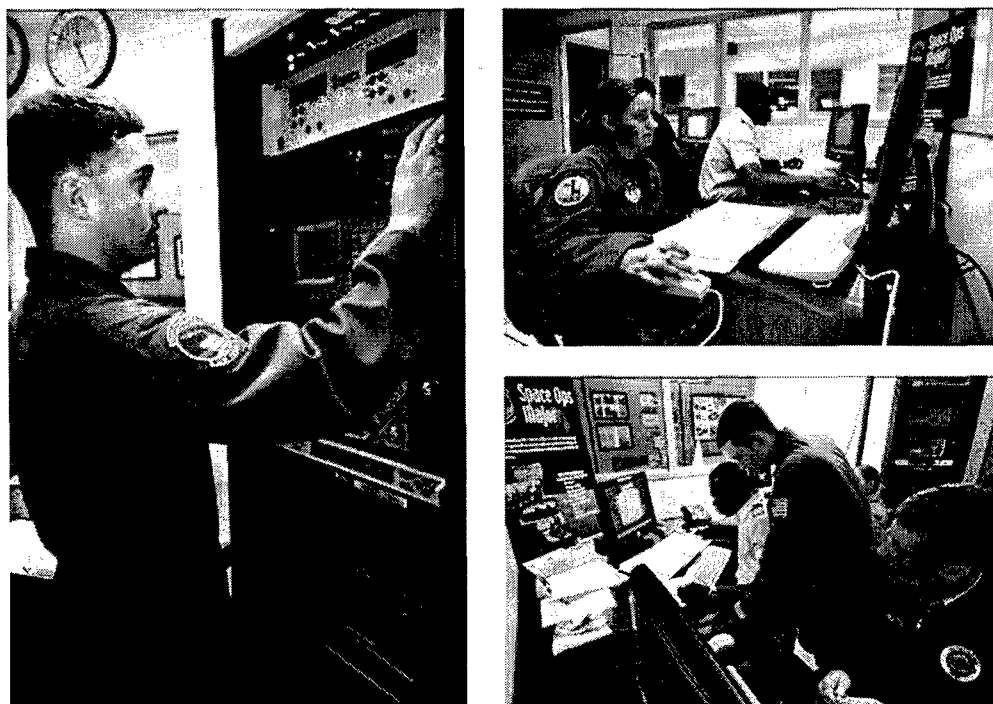


Figure 15. Cadets working in the FalconSAT Space Operations Ground Station.

IV. Cadet Reaction to the Program⁶

Assigning individual grades to a multidisciplinary group project of this size is a challenge. The grading system developed includes peer evaluations by members of each subdivision team and evaluations by the faculty mentors of these teams. The final grades are assigned by the senior faculty members in charge of the course. The overall reaction of the cadets to the program has been very positive even though everyone, including the faculty, is a volunteer. Many cadets come into their own in this type of course. Typical comments:

- "I believe I learned more than just space ops in this course. I was able to improve my leadership, written and oral skills. This course is probably the one I learned the most from in my cadet career."
- "Very challenging and rewarding."
- "The research that this course centered upon was the best research I have ever endeavored."
- "Great course, learned a ton!....Awesome opportunities, thanks."
- "Actually got to apply what I learned in class. A great learning experience."
- "Good operational/active duty experience."
- "I learned a lot about what happens on active duty and I realize there was a lot more that goes into Space Ops than I ever knew. What I liked most was that I could apply what I learned from previous classes."⁶

V. Future FalconSAT Programs

The Engineering Model phase of FalconSAT-3 has already been completed by the class of 2005. The Qualification Model and Flight Model of FalconSAT-3 will be completed by the class of 2006 for a launch on an Atlas V launch vehicle from Cape Canaveral in the Fall of 2006.

VI. Conclusions

Of course, all programs are judged by their results. Professional Air Force officers who have had the "Learning Space by Doing Space" experience while at the Air Force Academy are the real product of the FalconSAT program. The exposure to solving ill-defined problems in this program prepares cadets for the challenges of a professional military career. The space aspect of the program prepares them to join the cadre of space professionals.

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